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Uncertainties in decarbonising heat in the UK

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HIGHLIGHTS

- We identify the key uncertainties in decarbonising heat in the UK.
- A review on the current status of key heat supply technologies is presented.
- The significance of key uncertainties on heat technology costs are analysed.
- The impact on the development of the energy network infrastructure is assessed.
- The policy and incentives required to decarbonise the heat sector are examined.

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ABSTRACT

Heating is arguably one of the most difficult sectors to decarbonise in the UK's energy system. Meeting the 80% greenhouse gas emission reduction target by 2050 is likely to require that heat related emissions of CO_2 from buildings are near zero by 2050, and there is a 70% reduction in emissions from industry (from 1990 levels). Though it is clear that the use of the natural gas network will reduce over time, recent modelling suggests a limited residual role for gas by 2050 to help meet peaks in heat demand. High levels of uncertainty about the way in which heat will be decarbonised present a number of challenges to policy makers. This paper will explore the risks and uncertainties associated with the transition to a low carbon heat system in the UK as outlined by the 4th carbon budget review. The potential impact of key uncertainties on the levelised costs of heat technologies and the development of energy networks are explored using a sensitivity analysis approach. Policy changes required to decarbonise the heat sector are also examined.

1. Introduction

All of the anticipated pathways to a low carbon heat system will overtime, mean significant changes for the UK's energy infrastructure. The relative roles played by gas, electricity and heat networks in the supply of UK's heat demand will vary with policy interventions, technology costs, availability of investment and socio-economic uncertainties.

Heat constitutes the single biggest use of energy in the UK. Almost half (46%) of the final energy consumed is used to provide heat. Of this heat around three quarters is used by households and in commercial and public buildings. The heating demand is primarily met today using gas-fired boilers connected to the natural gas network (81%).

The UK's very low penetration of renewable technologies for heating is in part a direct consequence of ample supplies natural gas, availability of extensive gas transmission/distribution networks and the comparatively low upfront costs and efficiency of gas boilers.

Meeting the 80% greenhouse gas emission reduction target is likely to require that heat related emissions of CO_2 from buildings are near zero by 2050. Though it is clear that the use of the gas network will reduce over time, recent modelling suggests a role for gas in 2050 to help meet peaks in heat demand. There is significant amount of uncertainty in the strategic role envisioned for the future of the gas network (Hughes et al. 2013; Hughes and Strachan, 2010).

The government is progressing policy incentives that will reduce the heat demand of the existing building stock while promoting the

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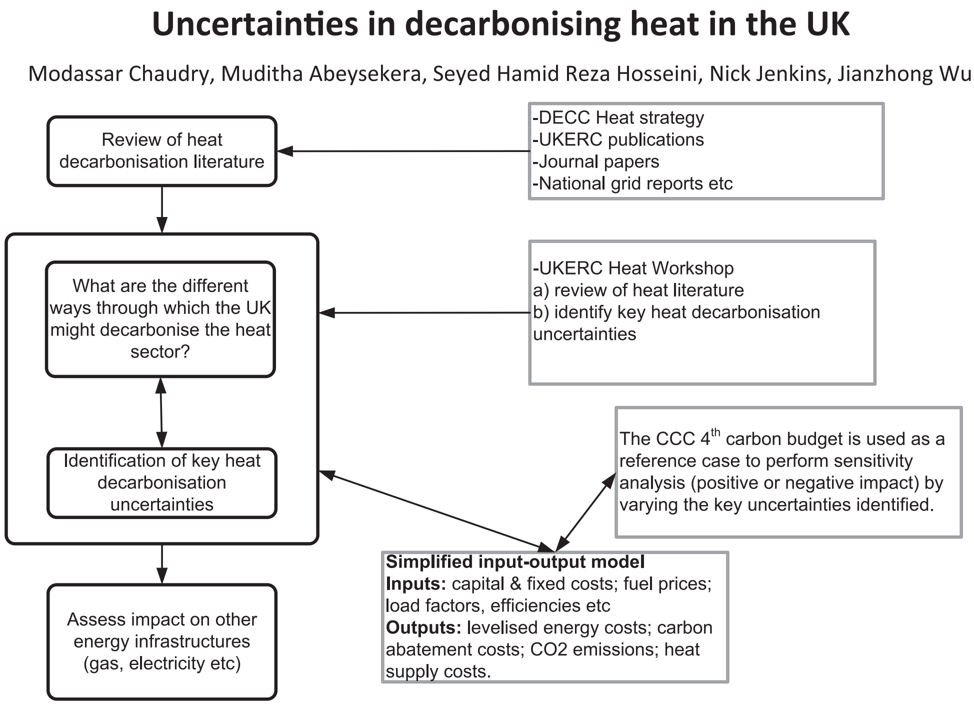

Fig. 1. Methodology for analysing uncertainties in decarbonising the heat sector (Chaudry et al., 2014).

uptake of renewable heating technologies. The recently deployed Green Deal is expected to remove the barrier of initial costs of energy efficiency improvements while the Renewable Heat Incentive (RHI) (DECC, 2015, 2013a; HM Government, 2014a) attempts to support market rollout of renewable heat technologies. However the success of these policy initiatives is uncertain and the impact on technology deployments are yet to be identified.

Heating is arguably one of the most difficult sectors to decarbonise in the UK's energy system. There is significant amount of uncertainty in what the UK heat supply might look like in the period from now to 2030 and beyond. High levels of uncertainty present a great challenge to policy makers to make sound strategic decisions about the future. It is essential to identify and manage these uncertainties in order to support plausible pathways to a low carbon energy system.

2. Objectives and methodology

The aim of this paper is to explore the risks and uncertainties associated with the transition to a low carbon heat system in the UK out to 2030 and investigate the potential impact of these uncertainties in the development of energy supply infrastructure (gas, electricity and district heating).

Specific research questions addressed are:

- What are the key heat decarbonisation uncertainties?
- What are the different ways (technologies) through which the UK might decarbonise the heat sector?
- How will these affect the development of the energy network infrastructure (gas, electricity and heat networks)?
- What policies/incentives are required to decarbonise the heat sector?

The issues addressed in this paper concerns operational, strategic and policy uncertainties. A pathway/sensitivity analysis approach is used to analyse these uncertainties in a systematic way (Davies et al., 2014).

2.1. Approach to analysis

Fig. 1 illustrates the methodology used to address the specific research questions.

The methodology combines rigorous literature reviews with quantitative modelling and is summarised as follows:

1. A literature review summarises the various ways in which the UK can decarbonise the heat sector. The DECC (Department of Energy and Climate Change) Heat Strategy, UKERC publications and other relevant literature are reviewed (Ekins et al., 2013).
2. The literature review aided by a workshop, facilitated the identification of key economic (cost), technical and policy related uncertainties associated with decarbonising the heat sector.
3. The CCC (Committee on Climate Change) 4th carbon budget technology uptake estimates were assessed using an input–output model. The model calculates levelised energy costs, carbon emissions, cost of carbon abatement and total costs (broken down into operational and capital costs for defined heat supply technology capacities) for year 2030 given inputs such as capital cost, fuel prices, various incentives and sectoral heat demands (domestic, service and industrial). The model was used to perform sensitivity analysis on the 4th carbon budget estimates by varying values of key uncertainties.
   The levelised costs are calculated by using the following formula:[1]

$$\text{Levelised energy cost } (\pounds/\text{MWh}) = (\text{annualised capital costs} + \text{fixed cost O\&M} + \text{fuel costs} + \text{carbon costs})/\text{total energy output}$$

The model was a valuable part of the overall methodology as it allowed quantification (though calculation of levelised costs; overall costs, carbon emissions etc.) and comparison for a range of

[1] Discount factor for capital costs was assumed to be 10% and load factors were used as part of the calculation of levelised energy costs.

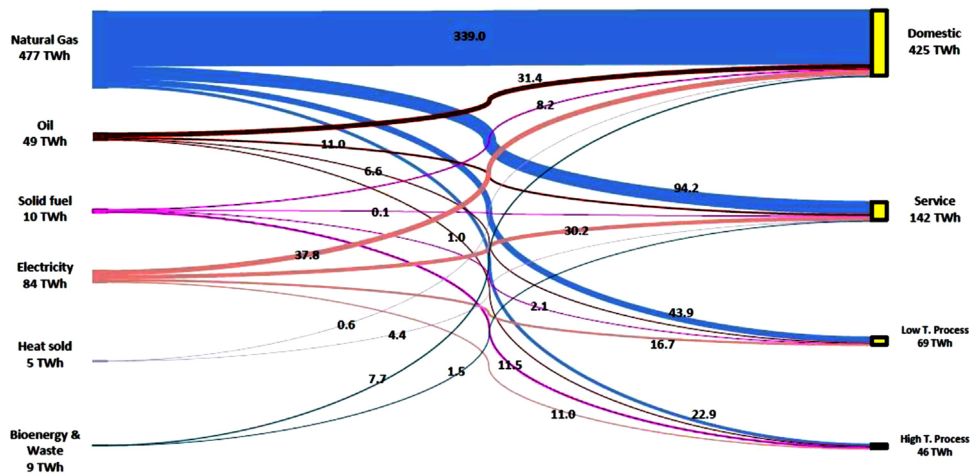

Fig. 2. UK's annual heat demand by different sectors and fuels (2012) (DECC, 2012a).

key uncertainties for various heat supply technologies highlighted during the literature review process. Other studies have employed techniques such as linking a series of sectoral (supply, demand; transport etc) models (simulation and optimisation) to analyse the impact of high levels of electrification of heat demand on electricity generation and the transmission infrastructure (gas and electricity) (Baruah et al., 2014).
The valuable aspect of calculating 'levelised energy costs' is that all costs are combined together on a £/MWh energy basis allowing comparison between various heat technologies.
The model is also very flexible in terms of being able to isolate (through sensitivity analysis) the effects of key inputs such as investment costs, operating costs, fuel costs and incentives on levelised energy costs.
The limitations of using the model and specifically the use of levelised energy costs are its inability to capture all economic externalities and the determination and use of appropriate discount rates, load factors etc (Gross et al., 2013).

4. An assessment was undertaken to identify the impact of technical uncertainties on the development of energy network infrastructure (gas, electricity and district heating).
5. The evidence was used to inform on policy implications; what needs to be done to minimise uncertainties (maximise opportunities) to decarbonise the heat sector.

3. UK heat demand and emissions

The current status of heat demand, the consumption of various fuels for meeting the heat demand in different sectors and heat related emissions are presented.

3.1. The current UK heat demand

The UK's heat demand can be broadly categorised as the,

a. Domestic heat demand.
b. Non-domestic buildings (service sector) heat demand.
c. Industrial heat demand.

Domestic heat demand accounts for 62% of the total annual heat demand in the UK in 2012. Non-domestic buildings (service sector)[2] accounts for 21% with 17% from industry (Fig. 2).

Both domestic and non-domestic building heat demands are at present predominantly met by natural gas fired boilers as shown in Fig. 2. It is important to note that heat supplied via heat networks accounts for a mere 0.5% and 3% in domestic and non-domestic buildings heat demand supply.

The seasonal variability is a key factor to be taken into account when analysing the heat demand. This is largely a concern in domestic and non-domestic (service sector) buildings where the winter heat demand is much higher than that in summer (Fig. 3).

The seasonal variability is important as a decision to electrify heating will have consequences on peak generation and network reinforcement requirements. The impact will be even more significant when considering meeting peak heat demand during extremely cold winters and with the potential drop in heat pump SPF (Seasonal Performance Factor[3]) during these conditions.

3.2. Heat related emissions

Heat related emissions accounted for around 32% of the total greenhouse gas emissions in the UK (182 Mt CO_2e) in 2009. Fig. 4 shows emissions by fuel types and sector (DECC, 2012a, 2012b) in relation to updated projections made by the CCC (CCC, 2013a, 2013b).

As observed, emissions from electricity are about 33% of total GHG emissions. Natural gas contributes the most at about 52% of total GHG emissions. It should be noted that the industrial sector has the most amount of indirect emissions.[4] Domestic buildings in 2009 accounted for around 47% of the total heat related emissions and non-domestic buildings to a further 20%. Heat related emissions from industry accounts for approximately 30% of total heat related emissions in the UK. The 4th carbon budget review estimates by 2030, approximately a 30% reduction in emissions from domestic buildings and over 90% reduction in non-domestic buildings could be delivered (CCC, 2013a, 2013b).

[2] Non-domestic sector refers to public buildings, schools, recreational and sports facilities, business complexes and all other buildings with heat demands excluding domestic buildings.

[3] SPF is the ratio of total heat output of a device per annum to the total input electricity per annum. In terms of definition, SPF is the same as Coefficient of Performance (COP), but COP is just a theoretical number since it is calculated and reported by manufacturer in laboratory test conditions whereas SPF is a realistic value which is obtained in operational conditions and it is more reliable to assess the performance of a device based on the value of SPF.

[4] Indirect emission includes those emissions that are not produced by the user as a result of burning an energy carrier and producing emissions at the place of consumption of the energy carrier.

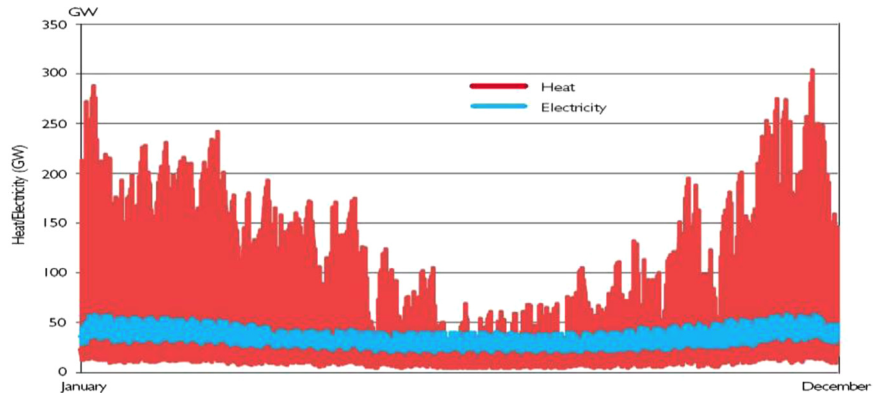

Fig. 3. Seasonal variation of the heat demand compared to the electrical demand (DECC, 2012c).

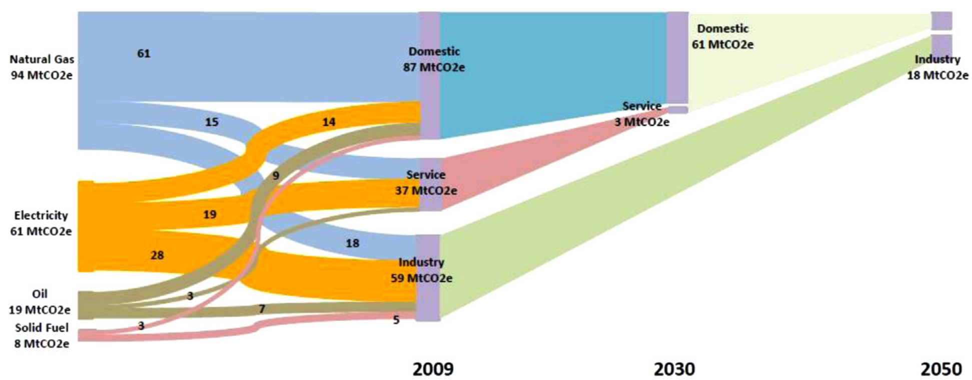

Fig. 4. Reduction of heat related emissions in each sector estimated by CCC projections (CCC, 2013a, 2013b; DECC, 2012a).

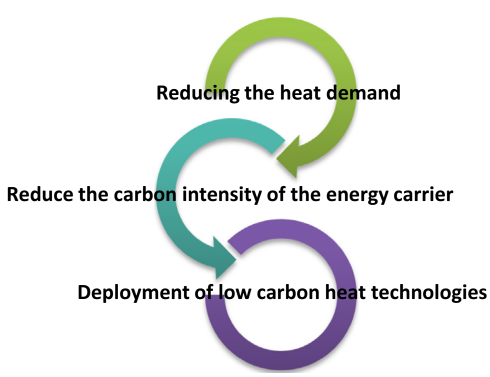

Fig. 5. Threefold approach to decarbonising heat in the UK.

4. Low carbon heat supply technologies

The three essential elements in achieving an effective reduction of carbon emissions in heat supply are shown in Fig. 5.

The relative carbon abatement potential of a particular technology is dependant upon the carbon emission intensity of the energy carrier used and the thermal efficiency of the heat supply appliance. The amount of emissions savings will further increase if the supplied heat demand is reduced.

4.1. Heat supply technologies

A review of the current status of heat supply technology options for meeting building space heating and hot water demand was undertaken and is summarised in Table 1. Technologies used for obtaining high temperatures in industry (e.g. Blast furnace) are not considered in this paper.

Several research studies (Cockroft and Kelly, 2006; Kesicki, 2012; Kannan, 2009) have compared technical and economic characteristics of different heat and power technologies for future building energy supplies in the UK.

The barriers and uncertainties associated with different heat technology uptake and domestic microgeneration in the UK were discussed in (Allen et al., 2008; Kannan, 2009). Although many technologies can be considered 'mature' globally, the UK market in low-carbon heat technologies is only just emerging. This is due to the dominance of the gas boiler market driven by the wider availability of natural gas. Low carbon heat technologies remain niche, either because the target market is small or due to immature supply chains and low customer awareness. (Allen et al., 2008; Delta-ee, 2012). A study by (Fawcett, 2011) explored the benefits of heat pumps from technological, economic, social and energy supply factors as well as addressing mechanisms for moving heat pumps from niche products to the mainstream.

It is also important to note the impact of technology turn over time on the adoption of low carbon heating systems. For example, average life time of a gas boiler can be up to 15 years, which means a customer who purchases a new gas boiler in 2015 is unlikely to consider a technology switchover until 2030.

The UK's building stock presents unique challenges in retrofitting new heat supply technologies. The considerations on technology suitability arise from space requirements, limitations of existing heat emitter and distribution systems, managing fuel supplies and planning regulations required in installing new low carbon heating systems (Allen et al., 2008; Delta-ee, 2012; Redpoint, 2012).

Table 1
Heat technology characteristics[a].

Technology	Status of maturity (levels – 5 being the most mature and 1 being the least)		Efficiency	Carbon performance (kg CO_2/MWh)	Upfront capital cost (£/kW)	Fixed costs (£/kW)
	Global market	UK market				
Gas boiler	5	5	90–95%	183–302	45–70	
Oil boiler	5	5	97%	246–407		
Coal boiler				471–700		
Biomass boiler (dom.)	4	2	90–95%	10–50	330–1667	19–30
Biomass boiler (non-dom.)					317–788	5–22
Biomass boiler (ind.)					44–509	14–22
Combined heat and power – gas (Large)	4	3	40–50%	150–450	657–864	48–80
Combined heat and power – gas (Small)					2363–4545	
Combined heat and power – fuel cell	2	2		128–550		
Micro CHP	2	2	85%		1025–3258	
Air source heat pump (ATA-non-dom.)	4	2	1.2–4 (SPF)	140–280	325–1415	1–19
Air source heat pump (ATW-dom.)					513–1963	4–19
Ground source heat pump (dom.)	4	2	1.5–5 (SPF)	29–240	940–1899	5–10
Ground source heat pump (non-dom.)					900–1560	1–9
Electric heating (dom.)			100%		166–187	2–3.5
Electric heating (com.)					197–221	1.5–11
Solar thermal (dom.)	5	4			681–2060	4–18
Solar thermal (non-dom.)					1170–1600	

[a] Values based on review of (AEA, 2012; AEA and Element Energy, 2012; Delta-ee, 2012; Edberg et al., 2011; Element Energy and NERA, 2011; Energy saving trust, 2010a; Frontier Economics and Element Energy, 2013; Hirschberg, 2003; NERA and AEA, 2009; Odeh et al., 2013; Poyry, 2009; Sweett Group, 2013; Woods, 2012; World energy council, 2004).

It was indicated by (Eyre, 2011) that conversion of the UK housing stock to electric heating would be “at best, extremely difficult, and, more likely, infeasible”. The paper emphasised the need for further research to understand the role of heat pumps in the UK residential sector and the impact on electricity grids.

Another option for meeting the heat demand in buildings is to connect to a heat network. Heat networks, often referred to as district heating schemes are a network of pipes carrying hot water from a central heat supply source to homes and businesses. The fundamental idea of district heating is to use local fuel or heat resources that would otherwise be wasted, in order to satisfy local customer demands for heating. Though theoretically most heat supply technologies can feed hot water to heat networks the choice is restricted by economics.

Apart from the technical and market challenges, there are significant socio-economic challenges to overcome for the adoption of low carbon heating systems. Several socio-economic research projects investigated the public attitudes and acceptability of low carbon heating systems in the UK (Parkhill et al., 2013; Chisholm, 2010; Drysdale, 2014). A UKERC study (Parkhill et al., 2013) reported that current electric systems (e.g. storage heaters) are viewed as undesirable while the public is unfamiliar with other forms of electric heating (e.g. heat pumps) and district heating (DECC, 2013e, 2013f). However, it was also noted that if cost and performance aspects of new heating systems are perceived to be comparable to current systems then a majority would consider these technology options.

5. Policy landscape and government strategy for heat decarbonisation

Analysis of uncertainties in decarbonising heating necessitates understanding the policy direction of government. The changes in the UK's government policy over time and the financial support programmes are summarised in this section.

5.1. Policy timeline

The government's energy policy portfolio provides a strategic framework for achieving the greenhouse gas emission reduction targets.

Fig. 6 shows the relevant policy papers (specific to heat decarbonisation) published and financial support schemes introduced since the climate change act was established in 2008. It should be noted that decarbonising heat goes hand in hand with energy efficiency improvements and decarbonising the electricity supply. However, policy papers relevant to energy efficiency and decarbonising the electricity sector are not investigated in this study.

The ‘Carbon Plan’ published in December 2011 (HM Government, 2011), sets out the government's vision for achieving the emissions reductions it is committed to in the first 4 carbon budgets. The fourth carbon budget, covering 2023–2027 was established in June 2011 and was reviewed in 2014 following advice from the CCC.

The CCC published an update for the 4th Carbon Budget recommendations in late 2013 (CCC, 2013a, 2013b) which presented new estimates. The estimates changed due to several reasons. These include gathering new and updated information and evidence, new energy modelling and related assumptions, etc. Table 2 shows a comparison between the original and updated targets.

5.2. Targets for heat sector emissions reductions

The first dedicated policy paper on heat was published by DECC in 2012 to outline the government's strategic framework for low carbon heat in the UK up to 2050 (DECC, 2012c). A year later, ‘The Future of Heating: Meeting the challenge’ was published to set out

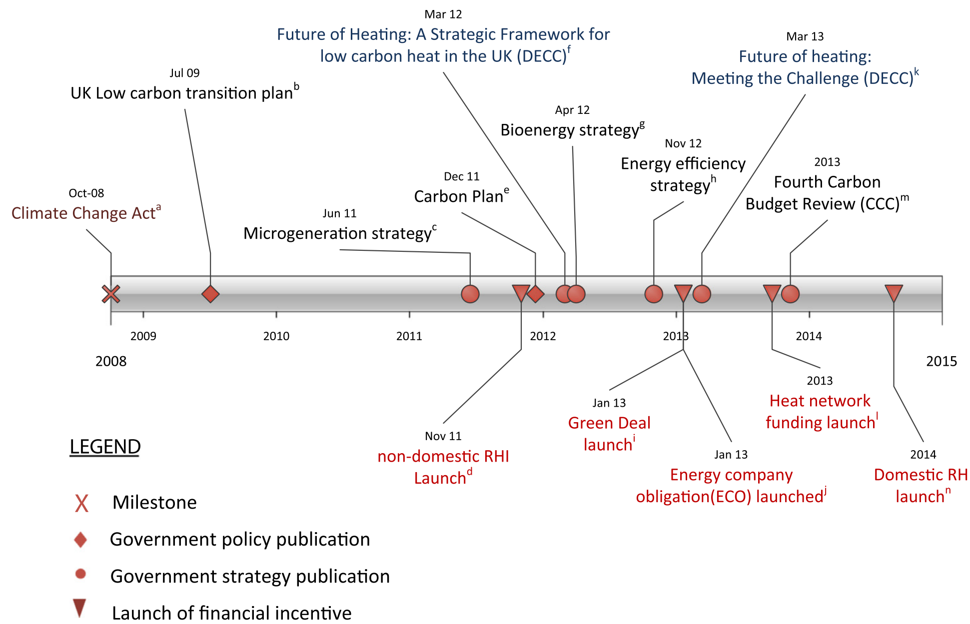

Fig. 6. Energy policy papers published with relevance to heat decarbonisation*. *a – (CCC, 2013c); b – (HM Government, 2009); c – (DECC, 2013d, 2011); d – (DECC, 2013g);e – (HM Government, 2011); f – (DECC, 2013c); g – (Department for Transport et al., 2012); h – (DECC, 2012d); i – (HM Government, 2014a); j – (HM Government, 2014b); k – (DECC, 2013b); l – (DECC, 2014); m – (CCC, 2013a); n – (DECC, 2013a).

Table 2
Comparison of original and updated 4th carbon budget (CCC, 2013a, 2013b, 2010).

	Item	Original target	Updated target
By 2020	Abatement potential (residential buildings)	17 Mt CO_2e	8.1 Mt CO_2e
	Residential buildings emissions		72 Mt CO_2e
	Total abatement potential (residential and non-residential buildings)	57 Mt CO_2e	17.2 Mt CO_2e
	Penetration of renewable heat	12% of total heat demand	
By 2030	Abatement potential (residential buildings)		27 Mt CO_2e
	Penetration of renewable heat	28% of total heat demand	
	Total heat delivered via heat pumps (TWh)	160	82
	Heat delivered via District heat (TWh)	10	30
	Heat delivered via Biomass (TWh)	13	
	Residential buildings emissions		61 Mt CO_2e

specific actions for the delivery of low carbon heat (DECC, 2013b, 2013c). In the midst of these, the 'Energy efficiency strategy', 'Microgeneration strategy' and the 'UK Bioenergy Strategy' were put forward to provide clear insight to the government's ambition in each sector for setting policy in the coming decades (DECC, 2012d, 2011; Department for Transport et al., 2012).

In addition to the government's cost-effective pathway modelling (DECC, 2013c), other parties have drawn alternative scenarios for achieving the emission targets. A plethora of scenarios of the energy system have been developed describing different paths towards achieving an 80% reduction in emissions by 2050. A majority of these scenarios investigate both the carbon emissions and cost impacts of this transition. Table A1 (Appendix) provides a high level overview of key stakeholder publications and diverse pathways presented in their analyses. The messages from these publications illustrate the ambivalence between key stakeholders on the future of heat supply in the UK. However, several common emerging messages can be identified,

- Energy demand reduction is essential for meeting emission targets.
- A substantial level of electrification of heating (via heat pumps) is expected.
- The future role of the gas network for domestic heat supply is uncertain.
- District heating will play an important role in heat supply decarbonisation.
- Widespread and early decarbonisation of the electricity system is required.
- Electrification of heating would increase both the peak and annual electricity demand significantly.

A summary of the financial support schemes introduced to promote low carbon heat supply are shown in Table A2 and A3 in the Appendix.

6. Analysis of the key uncertainties in UK heat infrastructure development

It is evident that meeting the carbon budgets and longer-term (2050) greenhouse gas emission targets will require a transformation in the way heat is provided today. Large scale deployment of low carbon heat technologies are plagued with uncertainties due to a range of technical, economic and market challenges. Fig. 7

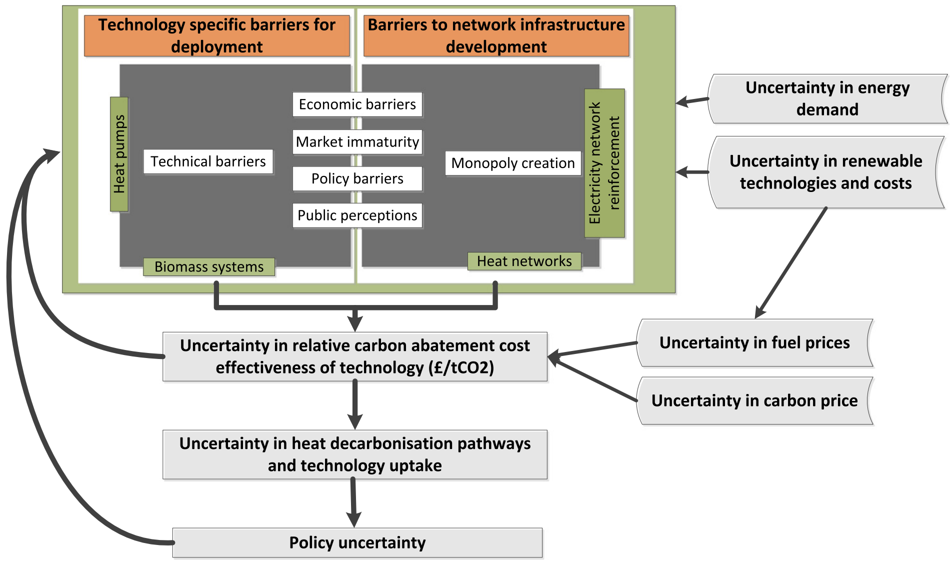

Fig. 7. Diagram of the inter-related nature of uncertainties in UK heat infrastructure developments (Chaudry et al., 2014).

illustrates the complex inter-dependant relationships of different uncertainty elements in the energy sector that impact the development of low carbon heat infrastructure.

Due to the relative immaturity of low carbon heat technologies in the UK market, each technology is met with a unique set of barriers for large scale deployment. These barriers are amplified by the uncertainties in policy direction, external factors such as fuel prices in the global market and uncertainties in achieving key decarbonisation goals in other parts of the energy sector (e.g. electricity sector decarbonisation).

A review of evidence on uncertainties effecting the deployment of two key low carbon heat technologies, heat pumps and district heating schemes and their impact on technology uptake is presented in Sections 6.1 and 6.2. In Section 6.3 various uncertainty elements such as capital costs, fuel prices, electricity grid emission intensity and heat demand are analysed with respect to their impact on overall costs and carbon abatement. Finally Section 6.4 outlines ways to manage the impact of uncertainties with a focus on the deployment of heat pumps and heat networks.

6.1. Uncertainties in heat pump deployment

Heat pumps (HP) are recognized as a key technology for decarbonising the hot water and space heating demands of domestic and non domestic buildings. Comparatively higher efficiencies (SPF around 2.5 for Air Source Heat Pumps (ASHP) and 3.0 for Ground Source Heat Pump (GSHP) systems) and the potential decarbonisation of the electricity supply make them highly attractive in the choice to replace gas boilers.

Even though heat pumps are a mature technology for heat supply in other parts of Europe, it is still a relatively new technology in the UK (20,000 installations per year in 2012 compared to 1.6 million gas boilers) (Frontier Economics and Element Energy, 2013).

The RHI for domestic customers (DECC, 2013a), is a government financial incentive to promote take up of heat pump systems and other low carbon heat technologies. The response to this financial support scheme is difficult to predict. Significant financial and non-financial barriers remain to be overcome in achieving the required levels of heat pump uptake. A number of technology challenges are yet to be addressed. Also, the repercussions on the electricity distribution network from a high rate of heat pump uptake will need to be carefully managed.

6.2. Uncertainties in the deployment of district heating

District heating has been deployed in the UK since the 1950's. However, it has achieved a relatively low market penetration and provides less than 2% of the UK heat demand today. This is in stark contrast to countries such as Sweden, Finland and Denmark which showed market shares for district heating grow considerably during the recent decades (Euroheat & Power, 2014).

Recently, there has been an increased interest in the potential of district heating to contribute to meeting the carbon budget targets. At the time of the first 4th carbon budget advice by CCC in 2010 (CCC, 2010), the estimated deployment of heat networks were quite low. The level of heat delivered via heat networks was expected at 10 TWh/yr by 2030 out of a total estimated potential of 90 TWh/yr. However, in the 4th carbon budget review in 2013 (CCC, 2013a, 2013b) this estimate was raised threefold to reach 30 TWh/yr by 2030 (6% of the total heat demand). A study (AEA and Element energy, 2012) for the 4th carbon budget review identified a greater potential for district heating deployment, at 160 TWh/year by 2050. The evidence base on the potential for district heating has strengthened over the past few years and a greater roll-out to 2030 is envisaged.

6.3. Impact of key uncertainties on costs and carbon abatement

There is a great deal of uncertainty with the cost and carbon abatement potential of heating technologies. CO_2 emissions will depend primarily on the degree of decarbonisation of the electricity system, fossil fuels burned, demand reduction and technology performance (efficiencies). Heat technology cost uncertainties are across a range of elements such as capital and fixed costs and fuel prices.

Fossil fuel prices, directly or indirectly account for a large percentage of overall running costs for a number of heat technologies. This will to a degree remain the case if electricity continues to be generated by fossil fuel plants (CCS etc) but less so if renewables command a large share of electricity generation. Network reinforcements, especially on the electricity system will be required in order to facilitate the decarbonisation of heat.

The impact of key uncertainties on indictors such as levelised energy costs, cost of carbon abatement and carbon emissions is explored using an input–output model through variations of key heat technology characteristics, heat demand and technology uptake in 2030.

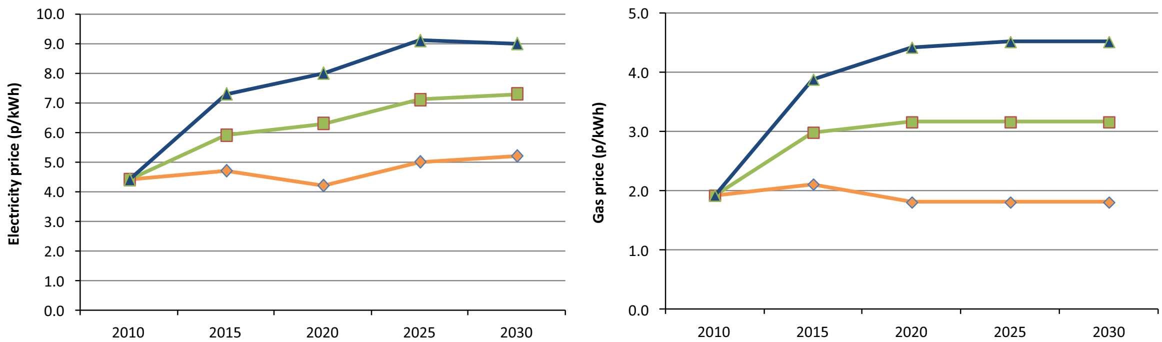

Fig. 8. Range of wholesale gas and electricity prices – low, central, high (CCC, 2013a, 2013b).

Table 3
Summary of heat technology characteristics in 2030[a].

Technology	Efficiency	Fixed operational costs (£/kW)	Capital costs (£/kW)
GSHP	1.5–5 (SPF)–Central: 2.5	5–10	940–1899
ASHP	1.2–4 (SPF)–Central: 2.5	4–19	513–1963
GT-CHP	40–50% (Heat)	48–80	Small: 2363–4545 large: 657–864
Gas boiler	90–95%	–	45–70
Biomass boiler	90–95%	19–30	330–1667

[a] Central capital/fixed costs and efficiencies are used for the reference case in 2030.

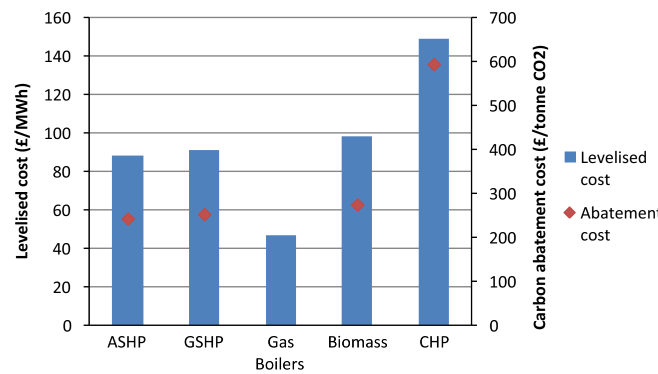

Fig. 9. CCC 4th carbon budget levelised and abatement costs in 2030 (derived from modelling).

Fig. 8 illustrates the projected range (low, central, high) of gas and electricity wholesale prices out to 2030 that are used in the analysis (CCC, 2013a, 2013b).

The summary of heat technology characteristics in 2030 is shown in Table 3.

6.3.1. CCC 4th carbon budget reference case (2030)

Technology uptake projections from the fourth carbon budget review were used to establish a benchmark for exploring the impact of key uncertainties. The levelised cost of energy (assumed carbon price of £70 CO_2/kWh by 2030; no other incentives were modelled in the reference case) and the relative carbon abatement cost for key low carbon technologies for 2030 (electricity grid emissions intensity: 50 g CO_2/kWh) were calculated as shown in Fig. 9.[5]

The calculated CO_2 emissions in the residential & commercial and industrial sectors are 64 and 65 Mt CO_2.

6.3.2. Analysis of key uncertainties

- *Variation in fuel costs.*
  Wholesale fuel costs contribute to a large percentage of the final cost of many heat technologies. Uncertainties in fuel costs as shown in Fig. 8 could lead to heat technologies going from being cost effective to being less attractive technology choices.
  Table 4 illustrates that heat pumps are better insulated to fuel price uncertainty compared with gas boilers and CHP (gas) technologies. This is mainly due to high heat pump efficiencies (SPF).
  The impact of gas price uncertainty on annual (2030) heat costs is large, running into the billions of pounds (Fig. 10). Electricity price variation has much lower impact on overall heat costs, again mainly due the relatively high efficiency of heat pumps.
  The uncertainties in fuel and electricity prices are due to a mix of exogenous and partially controllable factors such as the possibility of successful UK shale gas exploitation that could stabilise peak gas prices in medium term due to limited export pipeline/LNG facilities in the UK (as of 2015 only one pipeline was capable of operating in export mode) (House of Lords, 2014) and the prospect of large amounts of renewables connected to the electricity system possibly leading to somewhat volatile (weather dependant and lack of economical electricity storage facilities) and increasing (feeding through the high capital and operating/maintenance costs of renewables) electricity prices.
- *Variations in capital costs.*
  The estimated capital costs of low carbon heat technologies vary widely (Table 3). Capital costs for heat technologies such as ASHP/GSHP have a large impact on the levelised cost of energy especially in comparison to changes in the price of electricity (see Fig. 11). The reverse is true for gas boilers and gas based CHP technologies (fuel prices dominate).

Table 4
Impact of fuel price variations on levelised cost of energy (£/MWh).[a]

Scenario	ASHP	GSHP	Gas Boiler	CHP
Low gas price	–	–	−14.3	−28.1
High gas price	–	–	+14	+25.9
Low electricity price	−7.8	−8.4	–	–
High electricity price	+7.4	+6.8	–	–

[a] In comparison with reference levelised heat technology costs (central SPF values used).

[5] Levelised cost of energy and carbon abatement costs will differ from official CCC estimates as different capital and fixed costs and efficiencies were assumed (central values from Table 3 were used). The reference case (2030) is intended to serve as a base to analyse the impact of variation in elements such as capital costs, fuel prices and efficiencies of heat technologies.

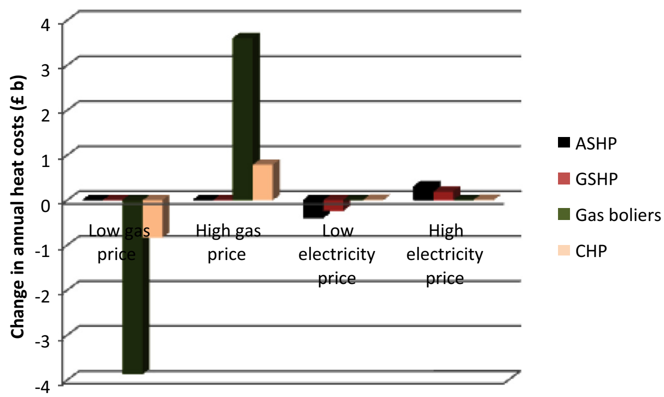

Fig. 10. Impact of fuel price changes on annual heat costs*. *In comparison with reference levelised heat technology costs.

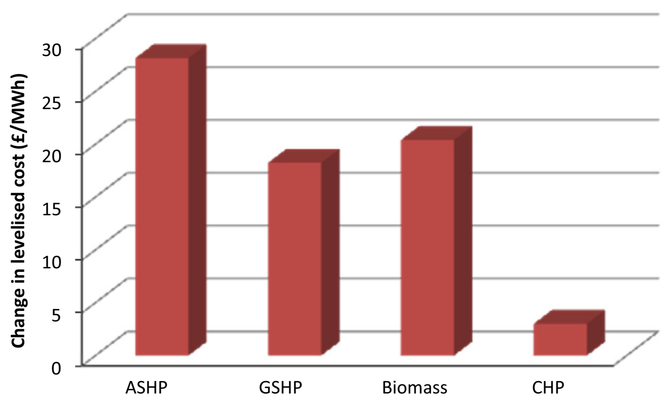

Fig. 11. Impact of high capital costs on levelised heat technology costs*. *In comparison with reference levelised heat technology costs.

Table 5
Impact of carbon price floor on levelised heat technology costs (£/MWh)[a].

Technology	£50/tCO$_2$	£100/tCO$_2$
ASHP	−0.4	+0.6
GSHP	−0.39	+0.61
Gas boiler	−3.4	+6.07
Biomass	−0.3	+0.55
CHP	−7.3	+10.7

[a] In comparison with carbon price of £70/tCO$_2$.

The reduction in capital costs for heat pumps could have an impact of approximately £1.7 billion per annum of total heat supply costs by 2030. With respect to biomass boilers modest saving can be expected with a reduction in capital costs of around £0.3 billion, this is mainly due to the low uptake of these in the 4th carbon budget review.

- *Impact of carbon price variations.*
  Table 5 illustrates that heat technologies dependant on fossil fuels suffer as the carbon price increases and gain the most as it drops. There is minimal change in levelised energy cost of heat pump technologies mainly due the virtual decarbonisation of the electricity sector (50 g CO$_2$/kWh by 2030).
  The annual cost of heat supply decreases by almost £2.5 billion as a result of a decrease in the price of carbon to £50/tonne CO$_2$ in 2030 to an increase of £3.8 billion if the carbon price increases to £100/tonne CO$_2$.
  The carbon abatement cost of a technology depends on many factors such as the engineering characteristics of the technology and of the electricity grid to which the new technology will be connected. The carbon abatement costs shown in Fig. 12 use gas boilers as the counterfactual technology.
  The analysis shows that the cost of carbon abatement of all low carbon heat technologies (heat pumps and biomass) decrease as the carbon price increases, but values of between £200–250/tonne CO$_2$ remain quite high.
- *Impact of heat demand variations.*
  The 4th carbon budget assumes a host of energy efficiency and demand reduction measures to be delivered by 2030. The realisation of these targets is difficult to predict. Table 6 shows the impact of a 20% increase in total heat demand in 2030 compared with the reference 4th carbon budget review case. The results show CO$_2$ emissions rising by approximately 14%. This places a large burden on the efficiency and demand reduction measures to live up to expectations.
- *Variations in heat supply technology characteristics.*

a. *Heat pumps.*

i. *SPF variations.*
Heat pump SPFs have a large impact on the levelised energy and annual heat pump running costs as shown in Table 7. If a heating system is considered to be in operation for 15–20 years then even a modest efficiency improvement can have a significant impact on energy bill savings to consumers; for example an improvement in average ground source and air source heat pump seasonal performance factors (SPF) to the upper values in the analysis could each result in a saving to consumers of approximately £500 million annually given the uptake assumed in the 4th carbon budget review.
The impact of SPF on carbon abatement costs is quite profound (Fig. 13). A high SPF pushes heat pump technology into the £130–150/tonne CO$_2$ range and could be even lower if capital and fuel costs fall.

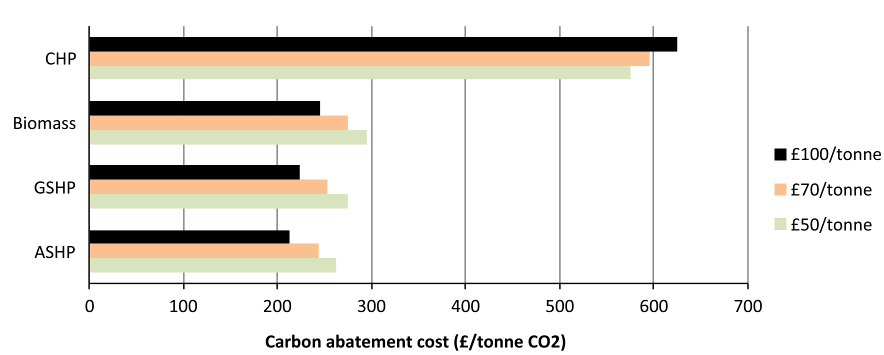

Fig. 12. Carbon abatement cost of heat technologies*. *Gas boiler is used as counterfactual.

Table 6
Impact of heat demand increase on CO_2 emissions Mt CO_2.[a]

Sector	Change in CO_2 emissions
Residential & commercial	+10
Industrial	+8.2

[a] In comparison with CCC 4th carbon budget review reference case heat demand.

Table 7
Impact of SPF on levelised costs and annual heat pump costs.[a]

Technology		Levelised cost (£/MWh)	Annual heat pump running costs (£b)
ASHP	SPF:1.2	+33	+1.45
	SPF:4	−10.9	−0.51
GSHP	SPF:1.5	+20.1	+0.57
	SPF:5	−15.3	−0.429

[a] In comparison with heat pump SPF:2.5.

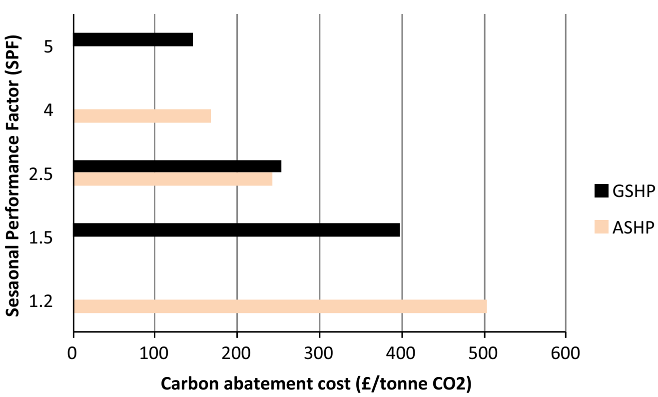

Fig. 13. Carbon abatement cost of heat technologies with respect to SPF.

Additionally the modelling shows SPF values lower than 2.5 could increase emissions by ~2 Mt CO_2 (given the uptake assumed in the 4th carbon budget review) and this impact would be greater if the electricity grid does not decarbonise to an intensity of 50 g CO_2/kWh by 2030.

ii. *Impact of different levels of heat pump uptake.*

The impact of increasing heat pump uptake in the residential and commercial sector by 50% in 2030 compared to the 4th carbon budget review is a 10% decrease in CO_2 emissions. Alongside this heat pump running costs would increase by over £3 billion annually by 2030 (Table 8).

a. *Biomass boilers.*

The Impact of increasing biomass boiler uptake in the residential, commercial and industrial sectors by 50% in 2030 compared with the 4th carbon budget review results in a 10% decrease in CO_2 emissions across all the sectors (Table 9). There is a decrease in the heat supply running costs this is mainly attributable to lower costs in the industrial sector by use of very efficient biomass boilers (replace gas CHP units that have a heat efficiency of between 30–50%).

- *The role of gas and electricity networks.*

Table 8
Impact of heat pump uptake on CO_2 emissions and annual costs.[a]

Technology	Heat pump uptake increase (TWh)	CO2 emissions (Mt CO_2)	Annual heat pump running costs (£b)
ASHP	+22	−7	+3.2
GSHP	+14		
	Total: +36		

[a] In comparison with CCC 4th carbon budget review reference case heat pump uptake.

Table 9
Impact of biomass boiler uptake on CO_2 emissions and annual heat supply costs.[a]

Sector	Biomass uptake increase (TWh)	CO_2 emissions (Mt CO_2)	Annual heat supply running costs (£b)
Residential & commercial	+7.5	−12.9	−0.8
Industrial	+20		
	Total: +27.5		

[a] In comparison with CCC 4th carbon budget review reference case biomass boiler uptake.

Table 10
Factors affecting future demand on the electricity network in decarbonising heat.

Technical
- Decarbonisation of electricity network
- Meeting the heat demand during peak winter periods
- Rate of uptake of heat pumps
- Future role of the gas network
- Development of heat networks
- Energy efficiency in buildings and industry
- Smart grid realisation

Economic
- Electricity network reinforcement
- Costs of electrical high temperature process heat
- Future gas / electricity prices
- Carbon price

Table 11
Impact of electricity system carbon intensity on carbon emissions (Mt CO_2).[a]

Sector	100 g CO_2/kWh	200 g CO_2/kWh
Residential & commercial	+1.5	+4.4
Industrial	+1	+3.1

[a] In comparison with electricity carbon intensity 50 g CO_2/kWh.

Both gas and especially electricity transmission and distribution systems will have a key part in helping to move to a decarbonised heat sector.

a. *Impacts on the electricity system.*
Several factors affect the future demand for electricity in meeting the heat demand in residential, services and industrial sectors as shown in Table 10.
The impact on carbon emissions as the carbon intensity of the grid increases from 50 g CO_2/kWh is minimal (see Table 11). This somewhat surprising result is mainly due to low level of heat pump uptake assumed in the 4th carbon budget review, heat demand reduction and relatively high values for heat pump SPFs.

Table 12
Electricity demand due to increase in heat pump uptake.[a]

Heat pump demand in domestic and commercial buildings sector (TWh)	Electricity demand (TWh)
72 (4th carbon budget review)	28.8
108	43.2

[a] Assuming SPF of 2.5.

An electricity system with a carbon intensity of 100 g CO_2/kWh results in a small increase in the levelised energy cost of heat pumps of approximately £2/MWh. This is mainly due to electricity system carbon intensity and therefore carbon costs having less of an impact compared with the relatively high efficiency of heat pumps (SPF values). But at the same time the carbon abatement costs increase by a larger amount especially for heat pumps. The results also show a small increase in overall heat system costs ($<2\%$). Overall CO_2 emissions increase by $\sim+2.5$ Mt CO_2 compared with the 4th carbon budget review reference case.

The impacts of a 50% higher heat pump uptake on electrical energy demand are shown in Table 12. In terms of additional generation capacity required to be connected to the grid (with respect to no heat pump uptake) could be between 10–15 GW.

The majority of scenarios and pathways for reducing overall CO_2 emissions assume a decarbonised electricity grid (50 g CO_2/kWh) which will allow the heat sector to be decarbonised through large scale adoption of heat pumps out to 2050. The analysis in this report does not disagree with this longer term aim.

What the analysis challenges is the notion that the UK must without fail decarbonise the electricity sector by 2030 for heat decarbonisation to occur at a later stage. The analysis does not support this given what could be called a drastic "reassessment" of heat pump penetration levels from the original CCC 4th carbon budget (143–72 TWh in the residential and commercial sectors with the slack taken up by heat networks that are not unduly impacted by electricity system decarbonisation).

On the other hand if heat pump uptake is much higher than envisaged in the CCC 4th carbon review then the impact of electricity decarbonisation on heat related emissions is greater.

These results are firmly based on heat pump efficiencies being at 2.5 SPF. Higher SPF efficiencies in 2030 will show a larger impact on CO2 emissions due to variation of electricity grid emission intensities.

The total impact of uptake of heat pumps on demand from the electricity network is relatively small in comparison to the total electricity demand expected by 2030. Therefore this level (4th carbon budget review) of heat pump uptake has a relatively low impact on overall electricity system reinforcements.

b. *Impacts on the gas system.*

The gas network will continue to play a key role by 2030 according to the 4th carbon budget review. Gas will play a vital role in helping to balance the electricity system with large amounts of renewables connected to the grid. Gas boilers are expected to continue alongside heat pumps in the form of hybrid systems to potentially meet the peak heat demand.

In 2012, the heat demand met by the gas network was $\sim$540 TWh. This will reduce to approximately 300 TWh/yr (4th carbon budget review) and to 250 TWh/yr if there is a 50% increase in heat pump uptake by 2030.

There are several factors that affect the role of the gas network and the extent to which it is going to be used; these are highlighted in Table 13.

Table 13
Factors affecting future role of gas network.

Technical
• Meeting the peak heat demand
• Uptake of heat pumps
• Developing heat networks
• Energy efficiency in buildings and industry
• Security of supply of alternative fuels
Economic
• Decommissioning
• Future gas / electricity prices
• Carbon price
• Iron Mains Replacement Programme
Market
• Gas exports and imports
• Shale gas
• Power generation demand

6.4. *Managing uncertainty*

6.4.1. *Heat pump uptake*

Significant barriers remain in achieving the required levels of heat pump uptake by 2030. Managing the uptake of heat pumps will require the government to use both 'carrots and sticks' type policy measures. These measures can be categorised as:

- *Enabling measures*: addressing behavioural barriers to uptake such as awareness and confidence.
- *Incentivising measures (Carrots)*: providing financial stimulus.
- *Mandating measures (Sticks)*: regulatory requirements.

Enabling measures can be put in place to manage uncertainties related to behavioural barriers in heat pump performance and awareness. Enhanced heat pump certification schemes mandating installers and consumer to obtain training can help delivering high standards in the design and installations of heat pump systems. This would improve the performance and thereby confidence and awareness of the technology (Frontier Economics and Element Energy, 2013).

The RHI is expected to drive the market for heat pump uptake up to 2020. Gas prices are expected to remain relatively unchanged by 2030 and therefore the counterfactual technology (gas boiler) will remain cost competitive in most building installations. Extending the RHI subsidy beyond 2020 might be required to maintain sustained growth in the heat pump market if consumers are to make savings by adopting heat pump systems. In many European countries it is reported that capital subsidy schemes are more common than RHI style subsidies (Frontier Economics and Element Energy, 2013). Another method of incentivising is to provide loan guarantees as those provided via the 'Green deal' scheme. By linking the green deal scheme to heat pump uptake policies it can be ensured that the installations take place at cost effective sites. A higher carbon price will also encourage the uptake of heat pumps by making gas and oil relatively more expensive. It is a good idea to initially focus on the off-gas market where the savings will be higher and replace the most carbon intensive heating systems. In the case of a high rate of uptake of heat pumps, the repercussions on the electricity network will need to be managed carefully.

Table 14
Summary of domestic RHI tariffs (Ofgem, 2014).

Technology	Domestic RHI (p/kWh)
GSHP	18.8
ASHP	7.3
Biomass boiler	12.2

6.4.2. Heat network uptake

Uncertainties related to the deployment of district heating schemes can be managed by addressing issues with market immaturity, up-scaling local authority skills and industry capabilities in the UK. The following were identified as potential solutions to deal with inconsistencies in the industry.

- Develop a model customer charter/code of conduct (standard forms of payment, service standards, treatment of bad debt and disconnection procedures etc.).
- Improve transparency in pricing of heat.
- Making available standard contract documentation.
- Making available a generic technical requirement specification.

Local authorities are key instigators of district heating schemes and should be better equipped to understand the potential benefits of heat network development and work with numerous stakeholders. Therefore the local authority skills and capabilities in managing district heating project should be up-scaled. It would be beneficial to mandate local authorities to consider potential for district heating in local planning. The ability to share information of experience in project development can be a key enabler to drive schemes forward.

Financial support for district heating from the government is important in unlocking the potential for district heating scheme deployments. Also a type of RHI payment for heat networks will enable developers to build a stronger business case for projects. Reducing the commercial risk of district heating scheme is key to project initiation. This could be managed by government putting in place mechanisms to underwrite risks to the developer.

6.4.3. Modelling policy measures

The RHI is the government incentive to encourage a switch to renewable heating systems for domestic and non-domestic buildings. Payments for the domestic RHI are based on meter readings of your heating systems annual heat use multiplied by the appropriate tariff (Table 14). These payments are for a maximum of seven years for domestic RHI and 20 years for non domestic RHI. The tariffs are initial values (Ofgem, 2014) and will be reduced as the overall budget for each scheme is approached. The budget for the RHI as whole is set at £430 million for 2015/16.

The RHI removes the barrier of additional heat technology costs, helping to create a level playing field between renewable and conventional heating technologies and widen the choice of heating options. It is expected that over time, the cost of renewable heating technologies will fall as technologies enter the mainstream and the benefits from economies of scale become more evident. But the renewable heat deployment levels in the 4th carbon budget review are relatively ambitious (even though they have been downgraded since the original 4th carbon budget announcement) given that heat pump and biomass boilers do not compete with gas boilers in domestic buildings even if favourable conditions occur such as low capital and electricity prices. Fig. 14 shows the levelised energy cost of technologies in domestic buildings.

Two policies for encouraging uptake of renewable heat technologies were assessed. Firstly carbon prices were modelled,

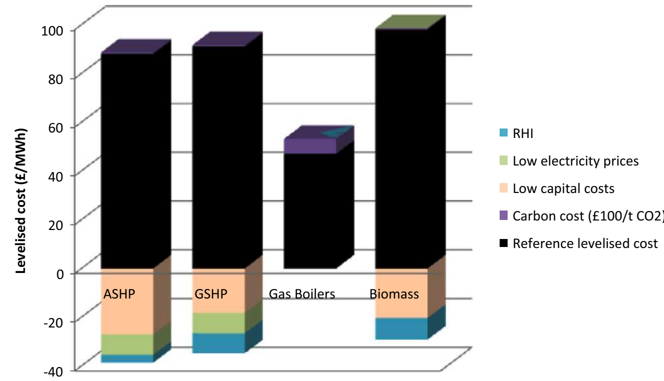

Fig. 14. Impact of policies and costs on levelised energy cost of heat technologies.

increasing from £70 to £100/tonne CO_2 (+£30 t/CO_2). This had a marginal impact on levelised energy costs of heat pumps and biomass boilers. The impact on gas boilers were appreciable but not enough by itself to lead to further investment in renewable heat technologies.

The second policy modelled was a continuation of the RHI through to 2030 by keeping the budget at 500 million per year (the budget is spread over a larger installed capacity of low carbon heat technologies therefore reducing the overall p/kWh RHI tariff) and at 4th carbon budget levels of heat pump and biomass uptake. This in itself narrows the gap between the levelised energy costs of air source heat pumps and gas boilers to near identical levels. Combined with extra carbon price support (+£30 t/CO_2) GSHPs are also within touching distance with gas boiler levelised energy costs.

Under these favourable conditions, carbon abatement costs drop to in the region of £150–175/tonne of CO_2 across all low carbon heat technologies. With technology learning especially with heat pump technologies (SPF improvements; lower capital costs) the carbon abatement costs will drop to below £100/tonne CO_2 (assuming a continuation of the RHI scheme).

7. Policy discussion and conclusions

The UK's climate strategy, through implementation of a series of carbon budgets will set the UK on a path to decarbonise the whole economy and meet the 2050 greenhouse gas emission target. The 4th carbon budget review attaches great importance to reductions in carbon emissions in the heat sector in the 2020s and therefore laying out the foundations to further reductions by 2050.

The aim of this paper is to explore the risks and uncertainties associated with the transition to a low carbon heat system in the UK out to 2030 and investigate the potential impact of these uncertainties in the development of the heat supply infrastructure.

The 4th carbon budget review ascribes prominent roles to demand reduction, efficiency improvements and to the deployment of heat pumps in efforts to reduce CO_2 emissions by 2030. The cost effective path assumes heat pump deployment of 72 and 10 TWh in the domestic/commercial buildings and industrial sectors. Other technologies such as heat networks and biomass boilers will also play key roles in helping to decarbonise the heat sector.

There is a great deal of uncertainty regarding the achievement of low carbon heat technology deployment levels and ultimately CO_2 emissions by 2030.

- *Uncertainties of heat pump deployments.*
  The performance of heat pumps is of paramount importance. The assumption is that most if not all types of heat pumps will

Table A1
Review of different stakeholder views on pathways for decarbonising heat.

stakeholder	Publication title	Author	Model used	Pathways modelled	Common emerging messages
Government	2050 Pathways analysis (HM Government, 2010)	HM government	2050 Calculator	A total of 6 different pathways were modelled and analysed with respect to varied electrification levels, a primary non-electric fuel scenario (biogas, biomass, power station heat, mix) and a pathway with less action on energy efficiency	• Ambitious per capita energy demand reduction needed • A substantial level of electrification of heating • Electricity supply may need to double and will need to be decarbonised • Sustainable bioenergy a vital part of decarbonising high-grade heating processes
	Future of heating: Meeting the challenge (DECC, 2013c)	DECC	RESOM and ESME	A run for the RESOM model was used to provide benchmark pathways for domestic, nondomestic and industry heat decarbonisation. The model was run for sensitivities and compared with ESME modelling	• A radical decarbonisation of heat for buildings and 60-70% reduction in emissions for industry required • Heat pumps and heat networks needed to achieve emissions reduction target • Role for gas in 2050, either in GAHP or in hybrid systems • Potential role for hydrogen to provide heat in industry and buildings
Utilities	Pathways for decarbonising heat (National Grid, 2012; Redpoint, 2012)	National grid/ redpoint	RESOM	Cost optimal pathways for decarbonising heat in a scenario where • UK can purchase international emission credits (Abatement cost cap scenario) • and where the UK effectively has to meet the emission target from abatement action only within UKare modelled and analysed	• Electrification of heat in buildings, facilitated by heat pumps is a critical component of decarbonising heat • Widespread and early decarbonisation of the electricity system required • Both peak and annual electricity demand rise rapidly from 2030 onwards, requiring timely reinforcements • Energy efficiency has a crucial role to play • To tackle the seasonal and diurnal swings in demand use of hybrid electric/gas heating and heat storage strategies important • A low risk way to achieve managing the swings in demand is by maintaining significantly reduced flows of gas in buildings or to make extensive use of heat networks • In sensitivities where gas forced out of buildings by 2050, costs for home heat and power rise by 10–15% • Key transition points in 2030s with rapid growth of electricity demand and roll-out of CCS, followed by wide scale use of hydrogen use in 2040's
Consultancies	Decarbonising heat: low carbon heat scenarios for the 2020's (NERA and AEA, 2010)	Report for CCC by NERA and AEA	Modelling framework developed by NERA and AEA	Benchmarking on a central scenario several alternative scenarios are modelled and analysed • An electrification strategy • a bioenergy strategy • a district heating strategy are explored.The scenarios are tested for sensitivities to discount rate, fossil fuel price, biomass availability and energy efficiency	• Low carbon sources could reduce emission from heat by one third by 2030 • Significant emission abatement could be provided at low or even negative cost • Attractiveness of heat pumps depend on improvements in the technology over the next two decades • Heat pumps are an attractive option for decarbonisation of space heating, complemented by bioenergy for high temperature heat • District heating route would require significant coordination and potentially changes to market arrangements • Failure to promote energy efficiency a significant risk
	Decarbonising heat in buildings: 2030–2050 (domestic and service sector) (Element	Report for CCC by element energy and	Scenario modelling	Starting from the CCC central scenario prediction for 2030 the modelling establishes a baseline scenario	• With continued growth in the UK's building stock the potential for reductions in overall thermal

Table A1 (*continued*)

stakeholder	Publication title	Author	Model used	Pathways modelled	Common emerging messages
	Energy and AEA, 2012)	AEA		for evaluation • A scenario where the existing policies are assumed to continue beyond 2030a scenario of high DH uptake • and a scenario where uptake of building level renewable heat is restricted are modelled	demand relative to today is limited • Projected total UK buildings heat demands in 2050 range from 416 TWh/yr (high efficiency) to 532 TWh/yr (low efficiency) • Complete shift in the heating market to renewable heating technologies • An order of magnitude drop in the carbon intensity of grid electricity relative to today's values • Abundant supply of ultra-low carbon electricity • Most robust low carbon heat pathway will involve a mix of technologies (electrification, district heating, biomass) • Around 80% of thermal demand is technically suited to DH • A maximum of 28% if thermal demand could be supplied by existing power stations • A maximum of 9% of non-industrial heating demand supplied by biomass boilers • Electricity demand for heating reach 100 TWh/yr under the policy extension scenario. • Peak heat demand estimated to be around 65 GW in the same scenario • Failure to decarbonise electricity supply and lack of suitability for renewable heat are the highest risks • Continued availability of relatively cheap gas could hinder the uptake of renewable heating technologies
	Pathways to 2050 – detailed analysis (Hawkes et al., 2011) (MARKAL model review and scenarios for DECC's 4th carbon budget evidence base)	AEA	MARKAL	MARKAL core run	• During the 4th budget period emissions intensity of the grid electricity would halve • Mass adaptation of heat pumps • Mass uptake of all cost-effective conservation measures • Notable component of demand response, is well underway in the 4th carbon budget period • All new installations of heating systems over the period from 2020 to 2035 • In the 4th budget period gas heating is still dominant
	2050 Pathways for domestic heat (DELTA-EE, 2012) (domestic heat)	DELTA Energy & Environment	Residential heat model developed by Delta-ee	Three potential pathways for low carbon heat in the domestic sector are modelled • Customer choice scenario where customers are allowed to choose their heating system based on upfront and running costs and physical fit • a electrification and heat network scenario where virtually all homes use either electric heating or heat networks • a balanced transition scenario where equal contribution from heat networks, low carbon gas appliances and electric heating is seen	• Customer choice scenario fails to meet the 2050 carbon targets. Gas boilers continue to be used in 19 million homes. Carbon emissions fall by 46% only. • Use of high electrification and heat networks can achieve 96% reductions in carbon emissions from the domestic sector • Balanced transition can achieve with less government intervention 90% carbon reductions • Keeping a variety of options open gives lower risks and potentially a lower cost path • Balanced transition avoids 12 million homes completely moving away from gas • Additional peak generation demand grows to 24 GW in balanced transition, rather than 48 GW (in the elec & DH) • Costs to reinforce the electricity distribution network are €8bn lower • Both scenarios require significant reduction in

					thermal demand, wide-spread expansion of heat networks, market maturity, decarbonisation of electricity grid, major distribution system upgrades and additional generation capacity • Balanced transition is relatively robust to sensitivities examined
	HHIC pathways for domestic heat (HHIC, 2012) (domestic heat)	HHIC & DELTA Energy		Three pathways are modelled • An all-electric scenario • a low carbon gas hybrid technology scenario • a balanced mix of technologies for different house types are modelled and analysed	• Government support required to bridge the gap for upfront cost of renewable heating technologies • Building investor confidence will be critical • Heat pumps and a suit of low carbon gas technologies make up the majority of the market by 2027 • By 2027 60% of homes will be condensing gas boilers, 5% of homes with district heating, 20% of homes with heat pumps and less than 2% on oil heating
UKERC	Comparing low carbon resilient energy scenarios for the UK energy system in 2050 (Anandarajah et al., 2009; Ekins et al., 2013)	UKERC	MARKAL/TIMES		• Greater increased efficiency and conservation • Residential heating by 2050 uses almost no natural gas • Heat pumps makes a major contribution to heating in all scenarios, supplemented by biomass and solar thermal • Electricity system needs to be decarbonised by 2030 by at least 80% • Active management of the electricity grid required to prevent high peak demands
Trade Organizations	Building a roadmap for heat: 2050 scenarios and heat delivery in the UK (Speirs et al., 2010)	CHPA	Review study	Examines the energy system scenarios to 2050 that have contributed to current government energy policy and develops an integrated scenario which seeks to utilise waste heat efficiently and diversify the means by which heat is provided to end users	• All electric future is low carbon but associated with continued reliance of fossil fuels and large losses of energy at the power generation stage • Challenges related to managing power flows, demand peaks and end-user adaptation of insulation, heat pumps and other measures • Use of CHP and DHN will assist a number of power flow and electric network issues

Table A2
Financial support schemes for promoting low carbon heat technologies and energy efficiency.

Category	Financial support scheme	Notes
Energy efficiency	Green deal (HM Government, 2014a)	Supports financing energy saving improvements to home or business (heating unit, insulation, drought proofing, double glazing, renewable energy generation)
	Energy efficiency directive (EUR-Lex, 2014)	
	Energy company obligation (ECO) (HM Government, 2014b)	Support from the energy company to improve home energy performance if on certain benefits or a low income, or for certain hard to treat properties
Deployment of low carbon heat technologies/infrastructure	Non-domestic renewable heat incentive (RHI) (DECC, 2013g)	Supports businesses, the public sector and non-profit organizations meet the cost of installing renewable heat technologies. Biomass boilers, heat pumps (ground source and water source), geothermal, solar thermal collectors and biomethane and biogas technologies are being supported.
	Domestic renewable heat incentive (RHI) (DECC, 2013a)	Supports individual households in meeting the cost of installing low carbon heat technology (ASHP, GSHP, biomass and solar thermal are to be incentivised via a feed in tariff mechanism)
	Heat network funding (DECC, 2014; DECC 2013f)	£6 million funding stream to support local authorities to develop technical proposals and financial evaluations of installing new heat networks or expanding existing ones
	Renewable heat premium payment	Financial support to installing renewable heating technologies at home. Solar thermal, heat pumps and biomass boilers are being supported

Table A3
Other financial instruments that through decarbonisation of the overall energy sector affects heat supply.

Financial instrument	Notes
EU ETS (European Commission, 2013)	The EU ETS works on the cap and trade principle. A cap is set on the total amount greenhouse gases that can be emitted by factories, power plants and other installations in the system. Within the cap, companies receive or buy emission allowances which they can trade with one another as needed
The climate change Levy (HM Government, 2011)	The climate change levy (CCL) is a tax on energy delivered to non-domestic users in the United Kingdom. Its aim is to provide an incentive to increase energy efficiency and to reduce carbon emissions
Carbon price floor (DECC, 2012e)	Minimum price for carbon (implemented through CCL); set at £16/ tCO_2 in 2013 increasing to £30/ tCO_2 by 2020 and £70/tCO_2 by 2030
Carbon reduction commitment (HM Government, 2011)	The CRC Energy Efficiency Scheme is a mandatory carbon emissions reduction scheme that applies to large non-energy-intensive organisations in the public and private sectors

have a SPF of at least 2.5. The reviews and modelling showed that lower SPF values could increase emissions by 2 Mt CO_2 (at uptake levels assumed by the 4th carbon budget review) and the impact would be greater if the electricity grid does not decarbonise to an intensity of 50 g CO_2/kWh by 2030. So there is a great emphasis on improving the performance of heat pumps through the period to 2020 and beyond. This can only be done if the uptake of heat pumps is relatively steady now and increases so technological learning can take place.
Currently the levelised energy cost of heat pumps is high when compared with gas boilers. This will most likely still be true by 2030. This is a major barrier for deployment of heat pumps and other technologies such as biomass boilers. Most of these technologies have high upfront capital costs that make a very large contribution to their levelised energy costs in comparison with incumbent technologies such as gas boilers. This issue is one that will only resolve itself with technological learning (cost reductions and efficiency improvements) and experience gained by installers to efficiently design heat based systems.

- *Electricity grid decarbonisation uncertainties.*
The analysis showed that given the deployment of heat pumps in the 4th carbon budget review the impact of not meeting the 50 g CO_2/kWh target by 2030 is not catastrophic for CO_2 emissions. But if heat pump uptake is larger than envisaged in the 4th carbon budget review and or efficiencies do not improve CO_2 emission reductions will not meet expectations. The aim is to reduce uncertainties by making sure that the power system is decarbonised so that performance and cost based uncertainties have a lower impact given potential pessimistic outcomes. In the longer term out to 2050 the heat system decarbonisation agenda very much rests on the shoulders of decarbonising the electricity grid to meet the 2050 CO_2 emissions target.
- *Heat network deployment uncertainties.*
The 4th carbon budget review provided a boost to heat network deployment levels from 10 to 30 TWh by 2030. Firstly there are significant economic barriers, mainly focussed around digging, laying of hot water pipes and high upfront capital costs for potential customers. Secondly, issues with public perception. There is a distinct lack of knowledge about heat networks (heating capabilities) including the charging methodology and awareness of services offered.
A review of heat networks showed that in terms of carbon abatement costs they are an effective solution in built up areas. But this was dependant on the level of electricity system decarbonisation.
- *Managing uncertainty.*

Enabling measures can be put in place to manage uncertainties related to public perception for technologies such as heat pumps and heat networks. For heat pumps, performance could be highlighted and awareness of both heat pump and heat networks could be increased by government and industry via exemplars.

Confidence in these technologies could be further enhanced by ensuring that installers abide by high standards in the design and installations of heat pump and heat networks.

Extending the RHI subsidy beyond 2020 might be required to maintain sustained growth in the heat pump market if consumers are to make savings by adopting heat pump systems. The modelling showed an extended RHI scheme could make heat pumps more competitive with the incumbent gas boiler but only if capital costs are consistently reduced to the low end of uncertainty range. This will need a steady uptake of heat pumps over the period to 2020 and beyond to allow learning to take place. This will most likely only occur if RHI support is maintained.

One can take this argument further and extend it to heat networks, it would be inconsistent for the government to continue to support the RHI for standalone technologies without offering a similar level of support for heat network development so that costs and risks through learning can be reduced and best practise in the system design process can improve over time.

The methodology used in this paper combined rigorous literature reviews with quantitative modelling. The model allowed analysis into the impact of variations of a number of heat supply technology uncertainties such as fuel prices, capital costs and efficiencies on levelised costs, overall costs and carbon emissions.

The limitations of using the developed model and specifically the use of levelised energy costs are its inability to capture all economic externalities and that the literature review needs to be constantly updated with up to date information in order to track how the uncertainties change and evolve with time.

The literature on the technical potential for district heating and its economic feasibility in the UK is limited and this would be an area of interest for future research. The techno-economic interactions between different energy networks (e.g. electricity, gas and district heating) are increasing both at the community and national level. A more thorough techno-economic study into the interdependent development of multi energy infrastructure for heat supply in the UK would also be a potential area for future research.

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Appendix A

See Tables A1–A3.

References

AEA, 2012. RHI Phase II-Technology Assumptions, Key Technical Assumptions for Selected Technologies. Report for Department of Energy and Climate Change. ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/66165/RHI_Phase_II_-_technology_assumptions.pdf⟩ (accessed 16.02.15.).

AEA, Element Energy, 2012. 2050 Options For Decarbonising Heat in Buildings, Final Report. Report for Committee on Climate Change. ⟨http://www.element-energy.co.uk/wordpress/wp-content/uploads/2012/04/Decarbonising-heat-to-2050-final-report_02.04.12.pdf⟩ (accessed 16.02.15.).

Allen, S.R., Hammond, G.P., McManus, M.C., 2008. Prospects for and barriers to domestic micro-generation: a United Kingdom perspective. Appl. Energy 85 (6), 528–544.

Anandarajah, G., Strachan, N., Ekins, P., Kannan, R., Hughes, N., 2009. Pathways to a Low Carbon Economy: Energy System Modelling. UK Energy Research Centre, London, UK. Report UKERC/RR/ESM/2009/001 ⟨http://www.ukerc.ac.uk/publications/pathways-to-a-low-carbon-economy-energy-systems-modelling.html⟩ (accessed 14.02.15.).

Baruah, P., Eyre, N., Qadrdan, M., Chaudry, M., Blainey, S., Hall, J.W., Jenkins, N., Tran, M., 2014. Energy system impacts from heat and transport electrification. Proc. Inst. Civ. Eng. Energy 167 (3), 139–151.

CCC, 2013a. Fourth Carbon Budget Review-part 2: The Cost-Effective Path to the 2050 Target. Committee on Climate Change. ⟨http://www.theccc.org.uk/wp-content/uploads/2013/12/1785a-CCC_AdviceRep_Singles_1.pdf⟩ (accessed 16.02.15.).

CCC, 2013b. Fourth Carbon Budget Review-Technical Report: Sectoral Analysis of the Cost-Effective Path to the 2050 Target. Committee on Climate Change. ⟨http://www.theccc.org.uk/wp-content/uploads/2013/12/1785b-CCC_TechRep_Singles_Book_1.pdf⟩ (accessed 16.02.15.).

CCC, 2013c. Meeting Carbon Budgets-2013 Progress Report to Parliament. Committee on Climate Change. ⟨http://www.theccc.org.uk/wp-content/uploads/2013/06/CCC-Prog-Rep-Book_singles_web_1.pdf⟩ (accessed 16.02.15.).

CCC, 2010. The Fourth Carbon Budget: Reducing Emissions Through the 2020s. Committee on Climate Change. ⟨http://archive.theccc.org.uk/aws2/4th%20Budget/CCC-4th-Budget-Book_plain_singles.pdf⟩ (accessed 16.02.15.).

Chaudry, M., Abeysekera, M., Hosseini, S.H.R., Wu, J., Jenkins, N., 2014. UKERC Energy Strategy Under Uncertainties-Uncertainties in UK Heat Infrastructure Development. Working Paper. UK Energy Research Centre, London, UK. Report UKERC/WP/FG/2014/005. ⟨http://www.ukerc.ac.uk/publications/ukerc-energy-strategy-under-uncertainties-uncertainties-in-uk-heat-infrastructure-development.html⟩ (accessed 15.02.15.).

Chisholm, F., 2010. Resident Opinion on the Use of Waste Process Heat for District Heating in Neath Port Talbot, Wales, (Master's thesis). School of Environment and Development, University of Manchester. ⟨http://www.tyndall.ac.uk/sites/default/files/Resident_Opinion_on_the_use_of_Waste_Process_Heat_for_District_Heating_in_Neath_Port_Talbot_Wales.pdf⟩ (accessed 04.03.15.).

Cockroft, J., Kelly, N., 2006. A comparative assessment of future heat and power sources for the UK domestic sector. Energy Convers. Manag. 47, 2349–2360.

Davies, G., Prpich, G., Strachan, N., Pollard, S., 2014. UKERC Energy Strategy Under Uncertainties-Identifying Techniques for Managing Uncertainty in the Energy Sector. UK Energy Research Centre, London, UK. Report UKERC/WP/FG/2014/001. ⟨http://www.ukerc.ac.uk/publications/ukerc-energy-strategy-under-uncertainties-identifying-techniques-for-managing-uncertainty-in-the-energy-sector.html⟩ (accessed 14.02.15.).

DECC, 2015. Increasing the Use of Low-Carbon Technologies. UK Department of Energy and Climate change. ⟨https://www.gov.uk/government/policies/increasing-the-use-of-low-carbon-technologies⟩ (accessed 25.02.15.).

DECC, 2014. Heat Networks Delivery Unit. UK Department of Energy and Climate Change. ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/375623/HNDU_overview_round4_Oct2014_PRINT_VERSION.pdf⟩ (accessed 24.02.15.).

DECC, 2013a. Domestic Renewable Heat Incentive: The First Step to Transforming the Way We Heat Our Homes. UK Department of Energy and Climate Change. ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/212089/Domestic_RHI_policy_statement.pdf⟩ (accessed 16.02.15.).

DECC, 2013b. The Future of Heating: Meeting the Challenge. UK Department of Energy and Climate Change. ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/190149/16_04-DECC-The_Future_of_Heating_Accessible-10.pdf⟩ (accessed 16.02.15.).

DECC, 2013c. The Future of Heating: Meeting the challenge, Evidence Annex. UK Department of Energy and Climate Change. ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/190151/16_04_DECC-The_Future_of_Heating-Evidence_Annex_ACCESSIBLE.pdf⟩ (accessed 16.02.15).

DECC, 2013d. Microgeneration Strategy Industry Action Plan. UK Department of Energy and Climate Change. ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/252483/Microgen_Strategy_Action_Plan_-_Final_Report.pdf⟩ (accessed 16.02.15.).

DECC, 2013e. Research Into Barriers to Deployment of District Heating Networks. UK Department of Energy and Climate Change. ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/191542/Barriers_tt_deployment_of_district_heating_networks_2204.pdf⟩ (accessed 16.02.15.).

DECC, 2013f. Summary Evidence on District Heating Networks in the UK. UK Department of Energy and Climate Change. ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/212565/summars_evidence_district_heating_networks_uk.pdf⟩ (accessed 16.02.15.).

DECC, 2013g. Non Domestic Renewable Heat Incentive (RHI). UK Department of Energy and Climate Change. ⟨https://www.gov.uk/non-domestic-renewable-heat-incentive⟩) (accessed 10.02.15.).

DECC, 2012a. Digest of United Kingdom Energy Statistics. UK Department of Energy and Climate Change. ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65881/5949-dukes-2012-exc-cover.pdf⟩ (accessed 16.02.15.).

DECC, 2012b. Emissions From Heat, Statistical Summary. UK Department of Energy and Climate Change. ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/140095/4093-emissions-heat-statistical-summary.pdf⟩ (accessed 16.02.15.).

DECC, 2012c. The Future of Heating: A Strategic Framework for Low Carbon Heat in the UK. UK Department of Energy and Climate Change. ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48574/4805-future-heating-strategic-framework.pdf⟩ (accessed 16.02.15.).

DECC, 2012d. The Energy Efficiency Strategy: The Energy Efficiency Opportunity in the UK. UK Department of Energy and Climate Change. ⟨https://www.gov.uk/

government/uploads/system/uploads/attachment_data/file/65602/6927-energy-efficiency-strategy–the-energy-efficiency.pdf〉 (accessed 16.02.15.).
DECC, 2012e. Electricity Market Reform: Policy Overview. UK Department of Energy and Climate Change. 〈https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48371/5349-electricity-market-reform-policy-overview.pdf〉 (accessed 06.03.15.).
DECC, 2011. Microgeneration strategy. UK Department of Energy and Climate Change. 〈https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48114/2015-microgeneration-strategy.pdf〉 (accessed 16.02.15.).
Delta-ee, 2012. 2050 Pathways for Domestic Heat, Final Report. 〈http://www.energynetworks.org/modx/assets/files/gas/futures/Delta-ee_ENA%20Final%20Report%20OCT.pdf.pdf〉 (accessed 16.02.15.).
Department for Transport, DECC, Defra, 2012. UK bioenergy strategy. 〈https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48337/5142-bioenergy-strategy-.pdf〉 (accessed 16.02.15.).
Drysdale, B., 2014. Demand Side Management: Flexible Demand in the GB Domestic Electricity Sector, (Ph.D. thesis). Institute of Energy, Cardiff University. 〈http://orca.cf.ac.uk/69859〉/ (accessed 04.03.15.).
Edberg, O., Barker, N., Stambaugh, J., 2011. Review of Technical Information on Renewable Heat Technologies, Report for the Department of Energy and Climate Change. AEA, UK. AEA Reference ED56353. 〈http://www.rhincentive.co.uk/library/regulation/1103AEA_Update.pdf〉 (accessed 16.02.15.).
Ekins, P., Keppo, I., Skea, J., Strachan, N., Usher, W., Anandarajah, G., 2013. The UK Energy System in 2050: Comparing Low Carbon, Resilient Scenarios. UK Energy Research Centre, London, UK. Report UKERC/RR/ESY/2013/001. 〈http://www.ukerc.ac.uk/publications/the-uk-energy-system-in-2050-comparing-low-carbon-resilient-scenarios.html〉 (accessed 14.02.15.).
Element Energy, AEA, 2012. Decarbonising Heat in Buildings: 2030–2050, Summary Report for the Committee on Climate Change. 〈http://www.element-energy.co.uk/wordpress/wp-content/uploads/2012/04/Decarbonising-heat-in-buildings-summary-report-final_02.04.12.pdf〉 (accessed 16.02.15.).
Element Energy, NERA, 2011. Achieving Deployment of Renewable Heat, Final Report for the Committee on Climate Change. 〈http://www.element-energy.co.uk/wordpress/wp-content/uploads/2012/05/CCC-Renewable-Heat-final-report_06.05.11.pdf〉 (accessed 16.02.15.).
Energy Saving Trust, 2010a. Domestic Low and Zero Carbon Technologies, Technical and Practical Integration in Housing. 〈http://www.begreensystems.co.uk/Images/CE317%20-%20Domestic%20Low%20&%20Zero%20carbon%20technologies_web%20final_2010%20edition.pdf〉 (accessed 16.02.15.).
EUR-Lex, 2014, European Commission Energy Efficiency Directive. Access to European Union Law. 〈http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1399375464230&uri=CELEX:32012L0027〉 (accessed 10.02.15.).
Euroheat & Power, 2014. District Heating and Cooling Statistics. Euroheat & Power, Brussels, Belgium. 〈http://www.euroheat.org/DHC—Statistics-4.aspx〉 (accessed 14.10.2014.).
European Commission, 2013. The EU Emissions Trading System (EU ETS). 〈http://ec.europa.eu/clima/publications/docs/factsheet_ets_en.pdf〉 (accessed 06.03.15.).
Eyre, N., 2011. Efficiency, demand reduction or electrification? In: Proceedings of the European Council for an Energy Efficient Economy (ECEEE) 2011 Summer Study. Energy Efficiency First: the Foundation of a Low-Carbon Society, pp. 1391–1399. 〈http://proceedings.eceee.org/visabstrakt.php?event=1&doc=6-010-11〉 (accessed 06.03.15.).
Fawcett, T., 2011. The future role of heat pumps in the domestic sector. In: Proceedings of the European Council for an Energy Efficient Economy (ECEEE) 2011 Summer Study. Energy Efficiency First: the Foundation of a Low-Carbon Society, pp. 1547–1557. 〈http://proceedings.eceee.org/visabstrakt.php?event=1&doc=6-388-11〉 (accessed 06.03.15.).
Frontier Economics, Element Energy, 2013. Pathways to High Penetration of Heat Pumps, Report for the Committee on Climate Change. 〈http://www.theccc.org.uk/wp-content/uploads/2013/12/Frontier-Economics-Element-Energy-Pathways-to-high-penetration-of-heat-pumps.pdf〉 (accessed 16.02.15.).
Gross, R., Heptonstall, P., Greenacre, P., Candelise, C., Jones, F., Castillo, A.C., 2013. An Assessment of Future Costs Estimation Methodologies in the Electricity Generation Sector. UKERC, REF: UKERC/RR/TPA/2013/001.
Hawkes, A., Narkeviciute, R., Morris, S., Solana-Rodriguez, B., 2011. Pathways to 2050 – Detailed Analyses. A Report for the Department of Energy and Climate Change. AEA, UK. AEA Reference ED56609 〈https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48073/2270-pathways-to-2050-detailed-analyses.pdf〉 (accessed 16.02.15.).
HHIC, 2012. HHIC Pathways for Domestic Heat. Heating and Hotwater Industry Council, Warwickshire, UK. 〈http://www.eua.org.uk/sites/default/files/HHIC_Domestic-Heat_18072013_LR.pdf〉 (accessed 16.02.15.).
Hirschberg, S., 2003. Comparative Analysis of Energy Systems. Paul Scherrer Institute, Villigen, Switzerland. 〈http://lrs.epfl.ch/webdav/site/lrs/shared/Document/hirschberg2.pdf〉 (accessed 16.02.15.).
HM Government, 2014a. The Green Deal, Energy Saving for Your Home. 〈https://www.gov.uk/green-deal-energy-saving-measures/overview〉 (accessed 10.02.15.).
HM Government, 2014b. Help From Your Energy Supplier: the Energy Company Obligation. 〈https://www.gov.uk/energy-company-obligation〉 (accessed 10.02.15.).
HM Government, 2011. The Carbon Plan: Delivering Our Low Carbon Future. 〈https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/47613/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf〉 (accessed 16.02.15.).
HM Government, 2010. 2050 Pathways Analysis. 〈https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/42562/216-2050-pathways-analysis-report.pdf〉 (accessed 16.02.15.).
HM Government, 2009. The UK Low Carbon Transition Plan. 〈https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/228752/9780108508394.pdf〉 (accessed 15.02.15.).
House of Lords, 2014. The Economic Impact on UK Energy Policy of Shale Gas and Oil. House of Lords, London, UK. 〈http://www.publications.parliament.uk/pa/ld201314/ldselect/ldeconaf/172/172.pdf〉 (accessed 06.03.15.).
Hughes, N., Strachan, N., Gross, R., 2013. The structure of uncertainty in future low carbon pathways. Energy Policy 52 (2013), 45–54.
Hughes, N., Strachan, N., 2010. Methodological review of UK and international low carbon scenarios. Energy Policy 38 (2010), 6056–6065.
Kannan, R., 2009. Uncertainties in key low carbon power generation technologies – implication for UK decarbonisation targets. Appl. Energy 86, 1873–1886.
Kesicki, F., 2012. Costs and potentials of reducing CO_2 emissions in the UK domestic stock from a systems perspective. Energy Build. 51, 203–211.
National Grid, 2012. UK Future Energy Scenarios. 〈http://www.nationalgrid.com/NR/rdonlyres/332FFA28-6900-4214-92BB-D3AD4FA5DC01/56611/UKFutureEnergyScenarios2012.pdf〉 (accessed 16.02.15.).
NERA, AEA, 2010. Decarbonising Heat: Low-Carbon Heat Scenarios for the 2020s. Report for the Committee on Climate Change.
NERA, AEA, 2009. The UK Supply Curve for Renewable Heat. Study for the Department of Energy and Climate Change. 〈http://www.rhincentive.co.uk/library/regulation/0907Heat_Supply_Curve.pdf〉 (accessed 16.02.15.).
Odeh, N., Hill, N., Forster, D., 2013. Current and Future Life Cycle Emissions of Key Low Carbon Technologies and Alternatives, Final Report. RICARDO-AEA, Oxfordshire, UK. Report reference ED58386. 〈http://www.theccc.org.uk/wp-content/uploads/2013/04/Ricardo-AEA-lifecycle-emissions-low-carbon-technologies-April-2013.pdf〉 (accessed 16.02.15.).
Ofgem, 2014. Tariffs and Payments for the Domestic Renewable Heat Incentive. Office of Gas and Electricity Markets, London, UK. 〈https://www.ofgem.gov.uk/environmental-programmes/domestic-renewable-heat-incentive/about-domestic-rhi/tariffs-and-payments-domestic-renewable-heat-incentive〉 (accessed 04.03.15.).
Parkhill, K., Demski, C., Butler, C., Spence, A., Pidgeon, N., 2013. Transforming the UK Energy System: Public Values, Attitudes and Acceptability – Synthesis Report. UK Energy Research Centre, London, UK. Report UKERC/RR/ES/2013/001. 〈http://www.ukerc.ac.uk/publications/transforming-the-uk-energy-system-public-values-attitudes-and-acceptability.html〉 (accessed 04.03.15.).
Poyry, 2009. The potential and costs of district heating networks, a report to the Department of Energy and Climate Change. 〈http://www.poyry.co.uk/sites/www.poyry.uk/files/A_report_providing_a_technical_analysis_and_costing_of_DH_networks.pdf〉 (accessed 16.02.15.).
Redpoint, 2012. Pathways for Decarbonising Heat. Report for National Grid.
Speirs, J., Gross, R., Deshmukh, S., Heptonstall, P., Munuera, L., Leach, M., Torriti, J., 2010. Building a Roadmap for Heat: 2050 Scenarios and Heat Delivery in the UK. Combined Heat and Power Association (CHPA), London, UK. 〈http://www.theade.co.uk/medialibrary/2011/04/07/e9a9f61d/Building_a_roadmap_for_heat_Full.pdf〉 (accessed 16.02.15.).
Sweett Group, 2013. Research on the Costs and Performance of Heating and Cooling Technologies, Final Report. A Report to the Department of Energy and Climate Change. 〈https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/204275/Research_on_the_costs_and_performance_of_heating_and_cooling_technologies__Sweett_Group_pdf〉 (accessed 16.02.15.).
Woods, P., 2012. ETI Macro Distributed Energy Project, Summary Report. Energy Technologies Institute, UK. 〈http://www.eti.co.uk/wp-content/uploads/2014/03/ETI_Macro_Distributed_Energy_Report_-21_March_2013_2.pdf〉 (accessed 16.02.15.).
World Energy Council, 2004. Comparison of Energy Systems Using Life Cycle Assessment. 〈http://www.worldenergy.org/wp-content/uploads/2012/10/PUB_Comparison_of_Energy_Systens_using_lifecycle_2004_WEC.pdf〉 (accessed 16.02.15.).